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- *Title:* Technology Showcase: Integrated Monitoring, Diagnostics and Failure Prevention. Proceedings of a Joint Conference, Mobile, Alabama, April 22-26, 1996.

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METHODS FOR DIAGNOSING THE FATIGUE DAMAGE RATE OF MATERIALS OF MACHINE ELEMENTS AND ESTIMATING THEIR FATIGUE LIFE

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Abstract: A pre-failure process of expiring the resistance of metal materials to elastic, plastic and unstable deformations in machine parts are similar to those in short-duration break tests of material specimens. Since the only similarity criterion for damage accumulation in a material element at different failure types is the ratio of characteristic times, the interconnected processes of expiring the resistance to elastic, plastic and unstable deformations in a material element and associated processes of accumulating damages can be estimated using the values of accumulated material damages in the short-duration break, namely, in the form of ratios of the times for elastic, plastic and unstable deformations to the total tim of specimen failure. The methods, developed on the basis of this regularity, for estimating materials' fatigue damage rate in short-duration break tests enable not only quantifying the conditions of fatigue failures of machine parts but also determining their operational fatigue life and thereby obviating the need for time-consuming, laborious and expensive tests of machine members.

Key words: Mechanical tests; resistance to deformation; damage rate; fatigue strength .

When determining mechinical properties of materials of aeronautical engineering parts it was noticed that in separate cases a reduced impact resistance was observed despite the fact that main material tensile-strength mechanical characteristics met the tec hinical specifications. In analysing tension test diagrams c ` specimens, substantial distinctions in the time to failure formation were revealed which corresponds to the time interval in the diagram between reaching yield and tensile strengths (all tests were conducted on the same tast machine with the same tape advance rate). Based on theoretical ideas concerning deformation and failure processes, one can conclude that this time interval in tension test diagrams caracterizes the resistance of the specimens' material to plastic deformation in the course of expiration of which crack nucleation and propagation take place under static loading. The minimum time for failure formation was observed in tension test diagrams of the specimens cut from the part with reduced impact toughness and the maximum one was observed in the diagrams of the specimens made of the same parts with the impact toughness corresponding to the requirements of technical specifications (Fig. 1).

Thus it was established that taken as the criteria characterizing the resistance of materials to elastic, plastic and unstable deforamations can be the durations of

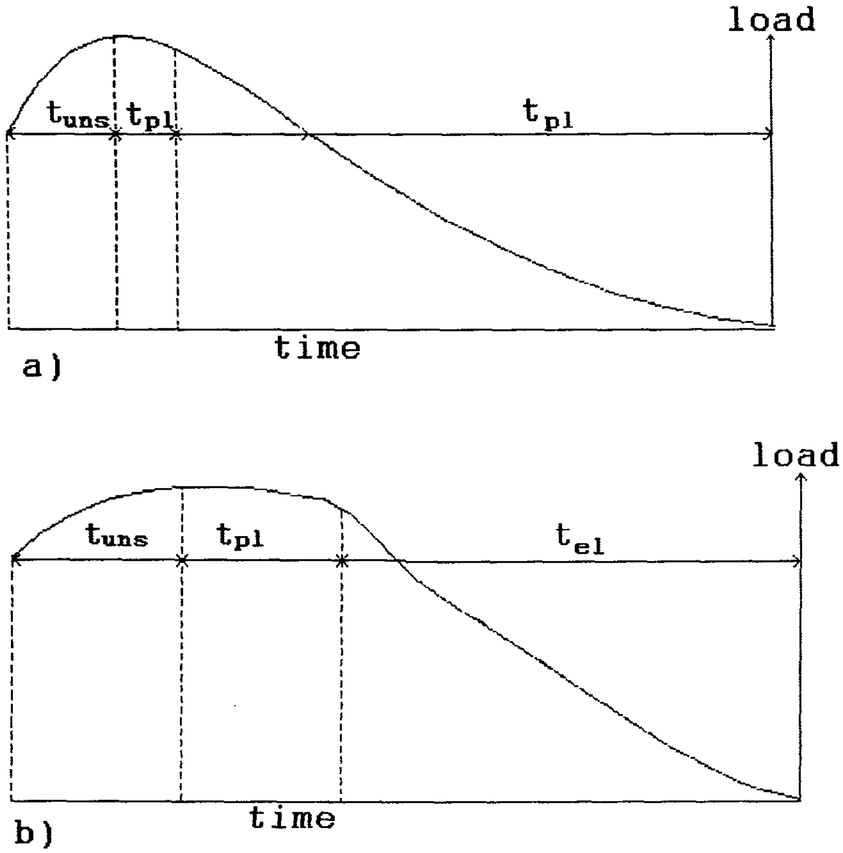

Fig.1 Tension tast diagram of the speciments cut from the material of the hydraulic accumulator cover which have an impact tonghness of no less than 50 j/cm^2 a) and no more than 50 j/cm^2 b).

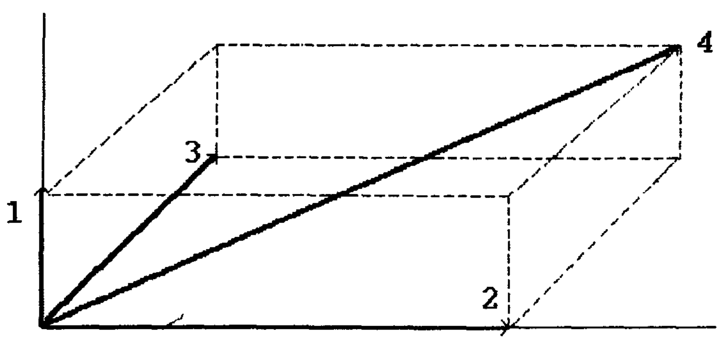

Fig.2 Element illustrating the limit fatique damage rate.

deformations determined from tension tast diagrams. The potentials inherent in any material of the resistance to elastic, plastic and unstable deformations are in sequence expirated in the course of any loading to failure. Hence, it is advisable to estimate them in the form of the ratios of the times for elastic t_{el}, plastic t_{pl}, and unstable t_{uns} deformations to the total time to failure t_f, while the accumulated damages a_d produced throughout the loading spectrum can be determined as a sum of these ratios squared:

$$\frac{t_{el}}{t_f}+\frac{t_{pl}}{t_f}+\frac{t_{uns}}{t_f}=1 \quad ; \qquad (1)$$

$$a_d=\sqrt{(\frac{t_{el}}{t_f})^2+(\frac{t_{pl}}{t_f})^2+(\frac{t_{uns}}{t_f})^2}. \qquad (2)$$

The regularities revealed became a prerequisite for developing a number of principally novel methods for diagnosing the fatigue damage rate of machine part' material under loading.

Method for determining the times for the nucleation and propagation of fatigue cracks in machine parts: In identifying the cause of the fatigue failure of a part for which the operating time T expressed in any units is known, the following times can be estimated based on the linear damage integration model represented in the form of (1) and (2): for the phase of the fatigue crack nucleation (T_{nuc}) during which the expiration of the resistance to elastic deformation goes on in the course of its loading:

$$T_{nuc}=\frac{t_{el}}{t_f}\cdot T; \qquad (3)$$

for the phase of the crack propagation T_{pr} during which the expiration of the resistance to plastic deformation of the material goes on at an apex of a crack as it

rows:

$$T_{pr}=\frac{t_{pl}}{t_f}\cdot T; \qquad (4)$$

for the phase of final failure (rupture) T_{fr}:

$$T_{fr}=\frac{t_{uns}}{t_f}\cdot T; \qquad (5)$$

The technical essence of the method for estimating the times to nucleation ant time to propagation of a fatigue crack in machine parts is as follows. In the vicinity of the fatigue fracture one cuts the pieces of the material of the part under examination and makes of them the specimens of standard shape and size for short-duration break

tests. Cutting is accomplished so that the specimen's longitudinal axis be normal to the part's fracture surface. The specimens thus made are to be tested for break with a constant deformation rate. During the loading up to a final failure one records time variations in the load in the form of a load-time tension diagram. In addition one measures the times for elastic t_{el}, plastic t_{pl}, and unstable t_{uns} deformations as well as the total time to specimen failure t_f. The time to crack nucleation T_{nuc}, time to fatigue crack propagation T_{pr} and time to final failure T_{fr} are calculated with formulas (3), (4), and (5), respectively. The persent [1] method was practically approved in a series of investigations and was shown to be rather effective as compared to the well-known fractograghy method for estimating the time for fatigue crack propagation.. In particular, this method was employed in identifying the cause of fatigue failure of the wing panel of an aircraft occured after 1927 flights.

In this case the nucleation sites of fatigue cracks were the rivet holes located on the lower panel surface near the wing trailing edge. Crack propagation went on in the cross direction, that is, the failure-producing stress-strain state was formed by longitudinal forces. Because of this the mechanical material properties of the lower wing panel were determined using the short-duration break tests of the specimens cut from the panel in longitudinal direction near the beginning of the panel failure. In the course of testing the specimens with a constant loading rate one recorded on the recorder strip the time changes of the load and measured the times for elastic, plastic and unstable deformations as well as the time to specimen failure. From the results obtained and measurements performed it was found that the material under examination had a tensile strength of σ_B = 600 MPa, a yield strength of σ_t = 550 MPa, a percentage elongation of δ = 7.9%, with the parameters of the resistance to elastic, plastic and unstable deformations being respectively:

$$\frac{t_{el}}{t_f}=0.39; \qquad \frac{t_{pl}}{t_f}=0.58; \qquad \frac{t_{uns}}{t_f}=0.03.$$

From the fact that the expiration of the panel's material resistance to elastic, plastic and unstable deformations had been in progress during 1927 flights it followed that for 751 flights the crack nucleation was taking place

($\frac{t_{el}}{t_f} \cdot T$=0.39 x 1927=751), for 1118 flights the fatigue crack was propagating due to expiring the resistance to plastic deformation, and,finally, for the rest of the flying time (58 flights) the accelerated propagation of the fatigue crack took place due to expiring the resistance to unstable deformation resulting ultimately in the wing panel rupture.

During the investigation the assessments were performed of the times to crack nucleation and crack propagation in the wing panel using the fractography method by taking into account the width of fatigue furrows on the microrelief of the panel

fracture surface.

As a result of measurements and calculations performed using this method it was found that the fatigue crack was propagating over 1111 flights and the time to crack nucleation, defined as the difference between the total flying time and the time to crack propagation, was equal to 817 flights. The result obtained by these two methods under consideration are in good agreement, but the method based on the linear damage integration model yields more plausible and comprehensive data on the time to crack nucleation and time of its accelerated propagation. As for the fractography method, it only allows the time of fatigue crack growth to be determined.

The method for determining the total number of cycles to failure : In operation, machine parts are as a rule subjected to complicated modes of loading where the sequence of amplitude and mean stress values vary randomly. Such a loading is referred to as the random loading.

In random loading the total number of cycles to failure depends on loading character, that is, maximum stresses, fraction of maximum stresses in the total number of cycles, mean stress, frequency of cycles, sequence of high and low stresses and other factors. This generated a need for developing methods for fatigue tests of materials in laboratory conditions with simulating main features of a random loading and for creating computational methods enabling the random-loading fatigue strength to be assessed using the results of the regular-loading fatigue tests.

For the effect of the loading mode on the metal fatigue strength to be taken into account, a variety of hypotheses are used. The most widespread is the linear cumulative damage hypothesis [2] :

The linear hypothesis is not always in good agreement with experimental data, but its simplicity and the absence of additional parameters favoured to its use in practice. Its main shortcomings lie in an insufficient accuracy associated with the impossibility to account for the loading time history and the fact that the stresses less than the fatigue strength are excluded from calculations as well as the laboriousness of accomplishing the test procedure.

Obtaining the totality of the damages accumulated throughout the loading spectrum have made it possible to simplify and improve the accuracy of the determination of the total number of cycles to failure using the results of short-duration break tests of a given material, measurements of times for elastic, plastic and unstable deformations and the total time to specimen failures [3].In so doing, the totality of damages accumulated in the material in loading to failure are calculeted from equation (2).

We take as an example the results of estimating the total numbers of cycles to failure of the material of the aircraft landing wheel hub. When investigating, made from the wheel hub, fabricated of the aluminium alloy AK6, were standard round specimens which were tested for short-duration break and fatigue using the method of combined rotation and bending. The tests were carried out at constant stresses of σ_i = 150 MPa, 200 MPa, and 300 MPa. The number of cycles to failure for the specimens were obtained to be respectively $108 \cdot 10^4$; $15 \cdot 10^4$ and $3 \cdot 10^4$.

The material specimens undergone to short-duration break were tested on the machine ИМ-4Р with a loading rate of 1.7 mm/min. In the course of loading to the point of failure, one recorded time changes of the load and measured the times for elastic, plastic and unstable deformations as well as the total time to specimen failures. As as result of tests and measurements performed the following mechanical properties of the wheel hub's material were obtained (Table I).

σ_B MPa	$\sigma_{0.2}$ MPa	δ_5 %	$\frac{t_{el}}{t_f}$	$\frac{t_{pl}}{t_f}$	$\frac{t_{uns}}{t_f}$	a_d
42.8	32.2	16.1	0.15	0.68	0.17	0.51
43.3	32.1	15.1	0.15	0.71	0.14	0.55
41.9	32.8	14.0	0.17	0.73	0.16	0.57

Table I Results of testing and measuring mechanical properties of the wheel hub's material (alloy AK6)

The total number of cycles to failure was obtained from the formula:

$$T_s = a_d\Big[\sum_1^n \frac{K_i}{T_i}\Big]^{-1}, \qquad \text{where } K_i = t_i \Big/ \sum_1^n t_i;\ K_1 = 0.024;\ K_2 = 0.12;\ K_3 = 0.85;$$

then $T_s = (1.22...1.37)\cdot 10^6$.

Thus, as a result of the tasts and measurements, it was found that the total number of cycles to failure of the wheel hub's material in random loading was $(1.22...1.37)\cdot 10^6$.

When using the prototype-related method the total number of cycles to failure was $(1.0...1.17)\cdot 10^6$ with the calculated total accumulated damage being 0.44...0.49. The use of the method proposed for determining the total number of cycles to failure simplifies the estimation procedure and increases the accuracy of the results obtained. It can be employed in diagnosing machine parts with the aim of determining their fatigue life and failure causes in operation.

Methods for determining the fatigue strength of metals : The methods presented are based on the following theoretical and experimental results. When a gradually increasing load is applied to a part or specimen, the deformation of the material goes on simultaneously in a set of glide planes and is accompanied by the bending and rotation of the glide planes. The vector of the stresses produced in reciprocal planes add up and reach limit values for the time less than the time to the failure of the part or specimen. In so doing, the process of reaching the limit stresses caused by the bending and rotation of glide surfaces is shortened in time due to

accumulating the damages produced by dislocation and disclination movements and by expiring the resistance to elastic, plastic and unstable deformations.Consider the behavior of the specimen's material in short-duration break. Let us denote by

$\frac{t_{el}}{t_f}, \frac{t_{pl}}{t_f}$ and $\frac{t_{uns}}{t_f}$ respectively the magnitudes of the vectors of accumulated elestic, plastic and unstable deformations (damages) of the broken specimen and the part (1,2,3 on Fig.2). Then the magnitude of the resulting vector was obtained from the formula (2) (4 on Fig.2.)

Depending on loading conditions (Fig. 2) the material element can lose stability as a result of either a critical change in volune (rotation instability) or a critical change in shape (translation instability). The translation instability is realized on reaching a critical dislocation density of the material in plane accumulations.Under the conditions of macroscopic deformations of a specimen or a part, this type of instability manifests itself at the boundary between elastic and plastic material behavior prior to the beginning of plastic yielding in the form of longitudinal translation in the tensile force field. The value of the maximum stress τ_{st} , required for longitudinally translating the material is equal to the scalar product of the vectors of tensile strength and limit elastic damage:

$$\tau_{st} = \frac{t_{el}}{t_f} \cdot \sigma_B \tag{6}$$

The rotation instability is realized on reaching a critical disclination density. Under the conditions of macroscopic deformation of a specimen or apart, this instability manifests itself prior to the formation of the neck due to the cross translation of the material which by that instant was in the state of longitudinal plastic yielding in the tensile force field. The value of the maximum stress τ_{cros} , required for the cross translation of the material is equal to the scalar product of the vector of maximum longitudinal stress into the unesulting vector of elastic, plastic and unstable deformations a_d:

$$\tau_{cros} = a_d \frac{t_{el}}{t_f} \cdot \sigma_B \tag{7}$$

When comparing the results of fatigue and short-duration break tests of the material it was found that the value of the maximum stress required for longitudinally translating the material in short-duration break is equal to the tensile and bending fatigue strengths of the material: $\tau_{st} = \sigma_{-1}$, and the value of the stress required for cross translation in break tests is equal to the torsion fatigue strength: $\tau_{cros} = \tau_{-1}$.

The results of tests and measurements are given in Table II.

Specimen's material	$\frac{t_{el}}{t_f}$	$\frac{t_{pl}}{t_f}$	$\frac{t_{uns}}{t_f}$	a_d	Calculated σ_{-1}/τ_{-1}	Experimental σ_{-1}/τ_{-1}
40XH2CMA	0.43	0.33	0.24	0.59	786.9 / 464.3	750-790 / 450-470
30XГCH2A	0.41	0.25	0.34	0.59	676.5 / 399.1	630-690 / 380-410
30XГCA	0.31	0.30	0.39	0.58	384.4 / 222.9	-
12X2H4A	0.35	0.23	0.42	0.59	427.0 / 251.9	-
O3XIIHIOM2T	0.49	0.14	0.37	0.63	739.9 / 466.1	720-785 / 450-480
B-95	0.39	0.58	0.03	0.70	234.0 / 163.8	190-240 / 130-170
AK4	0.38	0.62	0	0.73	163.4 /119.3	120-178 / 80-120
AK6	0.16	0.71	0.13	0.74	68.8 / 50.9	-

Table II. Fatigue strengths of materials calculated from the results of short-duration break and fatigue tests

Thus the above-presented results are indicative of the similarity of the processes of damaging the materials in short-duration break and cyclic loading. The distinctions lie in the fact that in the short-duration break the processes of expiring the resistance to elastic, plastic and unstable deformations are realized in the macrovolumes of the material, whereas in cyclic loading they go on in local volumes of the material.

The technical essence of the methods for determining tensile (bending) and torsion fatigue strengths is as follows[4,5]. One makes the specimens of standard shape and dimensions from the material to be studied in short-duration break tests. Then one carries out tensile tests with a constant deformation rate. In the course of loading to failure of the specimens one records time changes in the load P in the form of a load-time diagram. In so doing, one measures the times for elastic t_{el}, plastic t_{pl} , and unstable t_{uns} deformations as well as the time to failure t_f and the maximum load which the specimen withstanded during the loading. Based on the parameters obtained one calculates the tensile (bending) σ_{-1} and torsion τ_{-1} fatigue strengths:

$$\sigma_{-1} = \frac{t_{el}}{t_f} \cdot \frac{P_{\max}}{F}; \quad (8) \qquad \tau_{-1} = a_d \frac{t_{el}}{t_f} \cdot \frac{P_{\max}}{F}; \quad (9)$$

Where F is the cross-section area of the specimen's working portion; P is the maximum load.

The use of these methods substantially simplifies the procedure of determining material fatigue strengths as compared to conventional methods based on fatigue tests and provides the possibility of estimating these parameters using broken machine parts when identifying the causes of their breakdowns.

Bibliography:

1. Inventors' certificate No. 1696956, 1991, USSR. Method for estimating the fatigue damage rate of material. P.F.Tyugashov, V.A.Belokopytov, A.YE.Koltunov.

2. V.T.Troshchenko, L.A.Sosnovsky. Fatigue strength of metals and alloys. Handbook, Pt.I.- Kiev, Naukova Dumka Publishing House, 1987, pp.190-201.

3. Inventors' certificate No. 1744583, 1992, USSR. Method for diagnosing the fatigue failure of a machine part. P.F.Tyugashov, V.A.Belokopytov, A.Ye.Koltunov.

4. Inventors' certificate No.1733964, 1992, USSR. Method for determining the fatigue strength of materials. P.F.Tyugashov, V.A.Belokopytov, A.Ye.Koltunov.

5. Inventors' certificate No. 1665278, 1991, USSR. Method for determining the fatigue strength of material. P.F.Tyugashov, V.A.Belokopytov, A.Ye.Koltunov.